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(54) Title: TEMPERATURE-COMPENSATED QUANTITATIVE DIMENSIONAL MEASUREMENT DEVICE WITH PROGRAMMABLE IN-TOLERANCE/OUT-OF-TOLERANCE INDICATIONS

(57) Abstract

A computerized gauge (10) for measuring dimensions and temperatures of workpieces such as the diameter and temperature of a steel railroad car axle. It indicates the in-tolerance/out-of-tolerance condition of each measurement as well as the quantitative measurement value. Considering the predetermined coefficient of expansion of the workpiece (100), the gauge (10) calculates the dimension that the workpiece (100) would exhibit should it be thermally brought to a predetermined 59° F by convention, reference temperature. From the workpiece-temperature-compensated dimension resulting from such calculation, and from manually preset dimensional tolerance ranges, the axle (100) is indicated to be (i) oversized but repairable, (ii) within an acceptable size range, (iii) undesized but repairable, or (iv) undersized and unrepairable. The gauge (10) may further sense its own temperature and, in consideration of another predetermined coefficient of expansion as besuits the gauge, calculate a gauge- and workpiece-temperature-compensated dimension.

TEMPERATURE-COMPENSATED QUANTITATIVE DIMENSIONAL
MEASUREMENT DEVICE WITH PROGRAMMABLE
IN-TOLERANCE/OUT-OF-TOLERANCE INDICATIONS

BACKGROUND OF THE INVENTION

1.   Field of the Invention

The present invention concerns the dimensional
measurement of workpieces that undergo variations in
dimension with changes in temperature. The workpieces
are measured by gauges that themselves undergo varia-
tions in dimension with changes in temperature. The
present invention more particularly concerns measure-
ment systems that compensate for the temperature-
induced dimensional variation of workpieces, and/or the
temperature-induced dimensional variation of gauges, in
measuring the dimensions of workpieces with gauges.

The present invention further concerns the
indication of the in-tolerance/out-of-tolerance
condition of a measurement made on a workpiece by a
quantitative dimensional measurement gauge. The
present invention more particularly concerns variably
presetting any of (i) a reference dimension, (ii) a
tolerance range by independent preset of upper and
lower tolerance limits, and (iii) other variables prior
to qualifying the quantitative dimensional measurement
of a workpiece to be within or without tolerance
limits.

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2.   Background of the Invention

2.1   The Effect of Temperature on Dimensional
       Measurement

       It is known that certain materials,
5   particularly metals, expand and contract with
    temperature. This expansion or contraction is normally
    expressed as a coefficient of expansion. Such a
    coefficient of expansion is expressed in terms of
    dimension per unit dimension per degree temperature.
10   For example, a coefficient of expansion on the order of
    .000007 inches per inch per degree Fahrenheit is
    typical for certain ferrous metals.

       Dimensional changes with temperature obviously
    mean that a metal workpiece does not measure the same
15   dimensions at different temperatures. This makes it
    imprecise to determine the true, temperature-
    normalized, dimensions of the workpiece unless the
    workpiece is brought to a standard, reference,
    temperature. This standard, reference, temperature at
20   which workpieces are measured is often 59°F by
    convention, and is sometimes and for some purposes
    established at other particular temperatures.

       It is not always convenient to measure the
    dimensions of a workpiece while it is at the
25   predetermined reference. The workpiece may be either
    hotter or colder than the reference temperature and may
    correspondingly exhibit expanded or contracted (or vice
    versa) dimensional measurements. If the accuracy of
    quantitative dimensional measurement, or the accuracy
30   of qualifying a workpiece to some dimensional standard,
    is critical, then it is either necessary (i) to bring
    the workpiece to the predetermined, reference
    temperature at which the measurements may be performed,
    (ii) to compensate for the effect of the difference
35   between the actual workpiece temperature and the

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reference temperature on the dimension(s) of the
workpiece or (iii) to have a pre-determined dimensional
reference "standard" that is both at the temperature of
the part to be measured and that is also of the same
5   material, and to measure the difference between the
"standard" and the part.

If the workpiece has considerable thermal mass,
and/or it is not readily subject to be adjusted in
temperature, and/or a standard of identical material is
10 not available, then it may be more efficient, or even
mandated, that the workpiece should be measured at its
existing temperature. That dimension which the
workpiece would exhibit should it be brought to a
predetermined, reference, temperature may then be
15 calculated. This calculation requires knowledge of (i)
the measured dimension, (ii) the workpiece actual
temperature, and (iii) the thermal coefficient of
expansion for the material of the workpiece.

2.2   Previous Temperature-Compensated Dimensional
20   Measurement Systems

One previous example of a temperature-
compensated dimensional measuring system is shown in
U.S. Patent No. 3,594,909 for an APPARATUS FOR
MEASURING A DIMENSION OF A MEMBER to Schultz. The
25 workpiece being measured is, for example, a wide-flange
beam being formed in a rolling mill. The flange is
measured while it is still near its rolling temperature
of approximately six hundred degrees Fahrenheit
(600°F). The temperature-compensated dimensional
30 measuring system taught within the Schultz patent
obviates the need for permitting a sample piece of the
beam to cool to room ambient temperature before its
dimensions and/or symmetry may be checked for
unacceptable deviations from normal. In the apparatus
35 of Schultz, the temperature measurement means is a

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thermocouple probe. The probe contacts a workpiece
that is elevated in temperature. A computer receives
the signals from this probe and calculates the
temperature-adjusted workpiece measurements. These
5   measurements are, however, displayed only somewhat
inexactly as a trace registered upon a strip recorder.
Manual monitoring of the traces being recorded upon the
strip recorder allows recognition of the conformity or
nonconformity of the workpiece (typically a hot rolled
10   I-beam) to symmetry and dimensional standards.

The previous temperature compensation of
Schultz is primarily directed to producing and
displaying an output signal representative of dimension
upon a strip recorder when this output signal will be
15   within a predefined range, and when the resulting trace
will be observable for acceptable or unacceptable
deviations within this range, regardless of variations
in temperature of the workpiece for which dimension is
being sensed. Schultz is concerned with checking I-
20   beams for conformance with design standards; i.e., so
that each I-beam will carry its design load and will
mate with other I-beams of the same specification.
Schultz is not concerned with dimensional measurement
supporting the precision fitting of parts, as is the
25   present invention.

Schultz is not concerned with precise
quantitative dimensional measurement of a workpiece
while the workpiece is at a displacement temperature
from a predetermined, reference, temperature. Schultz
30   is not concerned that a measured dimension may be
converted to that temperature-normalized dimension
which a workpiece would exhibit should it be brought to
the reference temperature. The "compensation" of
Schultz is basically an "accounting" for rather large
35   dimensional deviations of a steel beam workpiece when

it is still near its rolling temperature of about
1600°F.

        Another previous example of a temperature-
compensated dimensional measuring system is shown in
U.S. Patent Serial No. 4,141,149 for a PORTABLE
COMPARATOR GAGE FOR MEASURING THE RELATIVE DEVIATION IN
THE DIAMETER OF CYLINDERS to George, et al. A portable
comparator gauge measuring the relative deviation in
the diameter of a cylindrical workpiece from the
diameter of a reference standard compensates for
inaccuracies in its measurement that are resultant from
variations in the temperature of the cylinder and the
gauge from a nominal temperature. The comparator gauge
of George, et al. has no intrinsic knowledge of the
nominal, or reference, temperature of measurement. It
must be calibrated to a standard, or reference,
cylinder that is supposed to be at the reference
temperature. When, and only when, the comparator gauge
of George, et al. is so calibrated to a standard
cylinder that is at a reference temperature can the
gauge later make an accurate, temperature-compensated,
comparative measurement of a workpiece cylinder.

        Alas, it is no easier to keep a standard, or
reference, cylinder or gauge block at a precisely
predetermined reference temperature than it is to
maintain a workpiece at this temperature. A standard
cylinder or gauge block is commonly taken onto the
factory floor, and is subject to assume temperatures
that are both (i) widely deviant from a reference
temperature, and (ii) time varying. It is desired to
make frequent calibration to the standard cylinder or
gauge block, regardless of its instantaneous
temperature. The gauge of George, et al. cannot be
calibrated to a standard cylinder that is at other than
the reference temperature. The quantitative

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dimensional measurement device in accordance with the
present invention will be seen to avoid this
limitation.

5   The present invention is concerned with precise
quantitative compensation of accurate (typically ± .001
inches) dimensional measurements of a workpiece when
the temperature of the workpiece over a wide range
(typically 70°F ± 50°F) is accurately known (typically
within ± 1°F). The reason that the present invention
10   is so concerned is not simply to garner measurement
numbers. The present invention is directed to better
enable a part "A" to mesh or fit into part "B". This
simple concept is important. If at 59°F a hole "A" is
2.0000 ± .0001 inches in diameter, and if at the same
15   59°F a shaft "B" of the same material is 1.9990 ± .0001
inches in diameter, then the shaft will (and not just
"should") fit within, and always fit within, the hole.
It is of great benefit to know that things will mesh or
fit together, and to know how well things will mesh or
20   fit together, as hereinafter explained.
2.3   The Requirement for Temperature-Compensated
         Dimensional Measurement
         The need for temperature-compensated
quantitative dimensional measurement is greater than is
25   commonly recognized. Commonly available measurement
reference standards, typically ground steel, are
accurate to ± .00001 inch. The dimensions of some
workpieces, such as the journals of railroad axles
hereinafter discussed, are augmented by process of
30   plating to accuracies of ± .00005 inches. These same
journals are diminished by process of machining to
accuracies of ± .0001 inch. (The journals may of
course be machined undersize and plated back to a
desired dimension.)

This degree of dimensional accuracy is common.
Yet these accuracies are completely overwhelmed by any
difference in workpiece temperature, and/or the
temperature of the frame of the measuring tool that

5   measures the workpiece, from a reference temperature.
As mentioned, steel has a coefficient of expansion on
the order of .0000068 inches per inch per degree
Fahrenheit. Consequently, for workpiece larger than 1
inch an uncompensated temperature variation of 10°F or

10   more can be the single greatest source of measurement
inaccuracy.

Uncompensated dimensional variation due to
temperature variation has been, in the opinion of the
inventor, a prime driver in the setting of dimensional

15   standards to which larger mechanical parts such as
journals and bearings are commonly constructed. The
nominal ± .001 inch tolerance to which these parts
(such as railroad axles, discussed hereinafter) are
sized is not the tolerance at which reasonably

20   optimized, let alone best, mechanical wear performance
is obtained. Mechanical wear of parts at tolerances of
± .0001 inch is markedly better than at lessor
tolerances, especially with modern lubricants. For
example, automobile manufacturer Volvo of Sweden has

25   gained a reputation for durability of automotive
mechanical parts which may be due, in part, to the
little-recognized fact that the parts of this
manufacturer are reportedly machined to better
dimensional accuracy than the Society of Automotive

30   Engineers (SAE) standards followed by the domestic U.S.
automotive industry.

If higher dimensional accuracies are
beneficial, and realizable, then why are these higher
accuracies not common? Why are the dimensional

35   standards of industry so liberal? A primary cause as

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to why higher dimensional accuracies than current
standards are not cost effectively realizable is the
difficulty in cost effective accurate control of
temperature. Accurate, ± 1°F, control of ambient
5   temperature is typically difficult and expensive.
Worse, a tight control of ambient temperature does not
invariably guarantee tight control of a workpiece
temperature because the workpiece temperature may be
affected by heats of machining and other processing.
10   Finally, temperature stabilization of workpiece thermal
masses takes time, and time is equivalent to cost in a
production environment.

As well as the sensitivity of dimensional
measurements of workpieces to temperature changes, it
15   should be well understood that the gauges and tools of
industry are themselves generally suffering much
greater dimensional variation due to temperature change
during use than any other single factor to which the
gauges or tools are commonly subject. That the
20   operative heads of drilling and milling machines change
size with variation in their temperature is obvious.
But even such tool faces as the cutter knife of machine
that cuts veneer from a log are unexpectedly subject to
undesirable change with temperature. A heat-expanded
25   veneer cutter knife must cut a thicker wood veneer
(else the cold knife would cut the veneer too thin),
reducing the amount of veneer that can be produced from
a log. Undesired dimensional variation with
temperature change thus directly translates into
30   reduced production of veneer. The veneer produced also
exhibits an undesirable increased variability of
thickness. This is but one of the more obscure of many
examples that generally show that dimensional variation
due to temperature change is an underecognized cost
35   driver both during production and during life cycle use

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of the products produced.

2.4   An Example of a Dimensional Measurement Problem
        Strongly Affected by Temperature Variation

One particular example of a workpiece upon
which it is desired to obtain precise dimensional
measurements while it is at a temperature differential
from a predetermined, reference, temperature is the
axle of a railroad car. The axle of a railroad car,
typically made of steel, is both large and heavy. It
exhibits a large thermal mass. The axles are normally
received into an indoors test environment from the out-
of-doors at temperatures which, in most regions of the
country during most portions of the year, are
distinctly neither at room temperature (typically 73°F)
nor the reference temperature (nominally 59°F).

The dimensions of the axle must be determined
at a reference temperature, nominally fifty-nine
degrees Fahrenheit (59°F). If the axles have become
warmer or colder than this reference temperature by
exposure to the environment, then a delay of many
hours, or days, would be encountered if the axles were
to be permitted to thermally stabilize at a 59°F
ambient temperature.

Because of these problems with temperature
stabilization of railroad car axles, the axles are
typically not quantitatively measured, but are rather
only compared to a reference gauge, or "Jo", block.
The Jo block is of the identical material to the axle
and is of a known dimension. This dimension is the
nominal standard for the journal of a railroad car
axle. A number of axles subject to comparison are
equalized at the same temperature as the "Jo" block,
typically at the room temperature of the test
environment. The temperature equalization is normally
aided by fans that blow air over both the "Jo" block

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and the axles for an extended period, typically
overnight.

In order to compare the axles a snap gauge
measurement tool is first zeroed to the "Jo" block.
5   The tool is then used to measure a plus (+) or minus
(-) size differential of an axle. The process
continues with repetitive rezeroings and measurements.
Ultimately the tolerances of the axles relative to the
"Jo" block are known even if the precise quantitative
10   dimensions of the axles are only but imperfectly known.

The utility of comparing an object to be
undersize or oversize relative to a reference is not as
useful as knowing the exact, temperature-normalized,
dimensions of such object. For example, the diameter
15   of an axle of a railroad car is typically desired to be
quantitatively measured to within ±.001 inch. This
accuracy in measurement is necessary to determine
whether axles are (i) repairable to be within required
normal dimensional range, (ii) issuable for use by
20   being qualified to be within normal dimensional range,
or (iii) subject to scrappage for being of unrepairable
dimensions. Typically, a railroad axle larger than
6.1915 inches in diameter is too large, but repairable.
An axle diameter between 6.1915 and 6.1905 inches is
25   within the acceptable tolerance range. An axle
diameter between 6.1885 and 6.1905 inches is slightly
too small, but normally repairable. An axle diameter
below 6.1885 inches is unsuitable for repair or
subsequent use.
30   The stringent requirement that the axle of a
railroad car should exhibit a diameter of 6.190 plus or
minus .0005 inches is due to the fact that dimensional
mismatch between the axle and its bearing can result,
at the high loads to which railroad cars are subject,
35   excessive rolling friction. Such rolling friction

results in thermal build-up and possible catastrophic
failure of the axle and/or axle bearings. In the
extreme case this can result in derailments. It is
believed .that as many as 60% of the catastrophic
5   failures of railroad car bearing axle assemblies may be
traceable to out of tolerance bearing race or axle
journal conditions.

        Meanwhile that the relatively large railroad
car axle must be measured very precisely, each change
10   in temperature of this axle of twelve degrees
Fahrenheit (12°F) causes a variation in the shaft
diameter of approximately .0005 inches, or fully one-
half of the total .001 inch tolerance range within
which the axle must be dimensionally qualified!
15   (Explicitly, 6.190 inches x .0000068 inches per inch
per °F x 12°F = .0005051.)

        Without temperature-compensated measurement, it
is obviously necessary not only that an axle should be
brought approximately to the predetermined, reference
20   measurement temperature, but that, indeed, the axle
should be brought very precisely to this temperature.
The aforementioned dimensions are those that the
standard railroad axle must exhibit at precisely fifty
nine degrees Fahrenheit (59°F). It is hard to make a
25   large thermal mass railroad car axle assume, and hold,
this precise temperature. Accordingly, some axles are
sent for rework, and some are even rejected,
incorrectly. Conversely, and more detrimentally,
certain axles for which the dimensions are improper may
30   otherwise be certified for use.

        Accordingly, the precise measurement of large,
dimensionally thermally sensitive objects such as
railroad car axles with high quantitative accuracy
typically requires performing and reperforming the
35   measurement process. Typically, a railroad car axle is

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measured several times before a confidence level can be developed that the correct measurements have actually been registered. This is obviously inefficient. Additionally, it is unsound safety practice that the measurement process should be so extremely dependent upon temperature variation that a difference in the temperature of the workpiece of a mere 48 degrees Fahrenheit (48°F) (corresponding to the difference between 6.1905 inches and 6.1885 inches) might cause an axle that is correctly subject to permanent scrappage to instead be issued directly for use without rework! An improved device for the quantitative dimensional measurements of workpieces that are dimensionally sensitive to temperature change is required.

2.5   A Requirement For Indication Of The In-
       Tolerance/Out-Of-Tolerance Condition Of A
       Measurement, And For Flexibly Presetting The
       Tolerance Of Such Measurement

Most times during use of a quantitative dimensional measurement gauge, with or without temperature compensation, the derived measurement quantity is of interest not for its absolute magnitude, but rather for being within, or without, some prescribed tolerance about some prescribed reference dimension. For example, a gauge is often used to measure a number of like workpieces in order to qualify each as being dimensionally within, or without, tolerance. The results of this determination may indicate, for example, that a workpiece is either to be reworked or scrapped or is instead issued for use as being of an appropriate dimension.

During the course of qualifying workpieces to be within, or without, a dimensional tolerance by quantitatively measuring their dimensions, it is useful if the measurement gauge automatically determines, and

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indicates, the in-tolerance or out-of-tolerance condition. A gauge that so indicates the results of an in-tolerance/out-of-tolerance determination is less likely to be misinterpreted, or misread in its

5   quantitative indication (if any is provided). A gauge that clearly indicates a go/no-go condition dependent upon the workpiece being either in-tolerance or out-of-tolerance may be used by a person of lower skill level, or by a person of equal skill level to produce

10   generally more reliable results, than can a gauge that only displays a quantitative dimensional measurement, and that requires the user to make the in-tolerance/out-of-tolerance determination from this displayed measurement.

15   An in-tolerance/out-of-tolerance indication by a measurement gauge may be as simple as showing a specific measurement on a scale having differentiated background regions, for example background regions that are green where a scale measurement reading is in-

20   tolerance, and background regions that are red when a measurement reading is out-of-tolerance. The problem with such a simplistic tolerance determination, and display, is that it does not besuit the generalized, multi-purpose, quantitative measurement of diverse

25   workpieces (although many workpieces of an individual type may be measured at one time in series). It would therefore be useful that a measurement gauge intended for generalized applications of quantitative dimensional measuring tasks might also be flexible in

30   the manner by which each of (i) a reference dimension, and (ii) dimensional tolerances about this reference dimension, could be set and indicated.

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SUMMARY OF THE INVENTION

The present invention contemplates compensating for the dimensional change of a workpiece, or of a gauge, or of both a workpiece and a gauge, with changes in temperature about a predetermined reference temperature during dimensional measurement of the workpiece with the gauge. The compensation is computed in consideration of predetermined dimensional sensitivity(ies) of the workpiece, of the gauge, or of both the workpiece and the gauge, to changes in temperature.

Devices and methods in accordance with the invention produce a workpiece-temperature-compensated, a gauge-temperature-compensated, or a workpiece- and gauge-temperature-compensated calibrated dimensional measurement of a workpiece by a gauge when neither the workpiece, nor the gauge, nor both the workpiece and gauge are at the reference temperature. Neither are the workpiece and gauge necessarily at the same temperature.

Those dimensional variations with temperature that are successfully and accurately compensated for during dimensional measurements in accordance with the present invention are typically a large, and often a largest, source of measurement error during many dimensional measurements of diverse workpieces with diverse gauges. Large measurement error due to uncompensated dimensional change of workpieces with temperature is especially true of workpieces that are large, that exhibit large thermal coefficients of expansion (or contraction), or that are of temperatures much different from a reference temperature. Large measurement error due to uncompensated dimensional changes of gauges with temperature is especially true of gauges that are large, that exhibit large thermal

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coefficients of expansion (or contraction), or that are
of temperatures much different from the reference
temperature.

The accuracy of the compensation performed by
the present invention is essentially dependent only on
(i) the accuracies of certain temperature sensing(s)
and (ii) a correct knowledge of certain pertinent
thermal coefficient(s) of expansion. The compensation
accuracy is typically very high, relegating errors in
dimensional measurement that are due to temperature
deviation to magnitudes at or below other sources of
measurement error. This simple concept is of great
significance in the real world. To repeat, the
accuracy of the compensation performed in accordance
with the invention is typically so good as to make
dimensional measurement accuracy to be primarily
dependent upon the accuracy of gauge blocks and
calibrated gauges, and not upon the temperatures of
gauge blocks, gauges, and/or workpieces.

In accordance with a first aspect of the
invention, a portable workpiece-temperature-compensated
dimensional measuring device includes a gauge for
measuring a dimension of a workpiece. The gauge
typically includes a dimensional measurement assembly
(such as a dial indicator or a linear variable
differential transducer) moving relative to frame by
contact with the workpiece. The gauge quantitatively
measures a workpiece dimension, typically its outside
or its inside diameter. Three point snap gauge, rocker
gauge, and other common gauge configurations are
suitably employed.

The device further includes a first thermal
sensor, typically a thermistor. The thermal sensor is
preferably held by the gauge in thermal communication
with the workpiece. It measures the temperature of the

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workpiece as a first temperature.

The device further includes a computer, preferably a digital computer and typically a microcomputer. The computer receives the dimension measurement from the gauge and the first temperature measurement from the first thermal sensor. In consideration of a predetermined first dimensional sensitivity of the workpiece to temperature variations about a predetermined reference temperature, the computer computes the temperature-compensated dimension that the workpiece would measure to and by the selfsame gauge upon such times as the workpiece was to be at the predetermined, reference temperature.

The workpiece-temperature-compensated dimension is optionally displayed, typically by a digital display.

In accordance with still another, second, aspect of the invention, the portable workpiece-temperature-compensated dimensional measuring device may be further adopted so as to compensate for its own dimensional self-variation with temperature. In this case the device further includes a second thermal sensor, typically an active semiconductor electronic temperature sensor. The second thermal sensor is in thermal communication with the gauge for measuring its temperature as a second temperature.

In this case of compensating for the gauge temperature the computer further receives the second temperature measurement from the second thermal sensor. The computer now calculates, in further consideration of a predetermined second dimensional sensitivity of the gauge to variations in temperature about the predetermined reference temperature, that temperature-normalized dimension that the workpiece would measure to and by the selfsame gauge upon such times as both it

and the gauge were to be at the predetermined reference
temperature.

The first and second aspects of the invention
can be reversed. Each of gauge-temperature-
5   compensation and workpiece-temperature-compensation can
be performed independently and exclusively of the
other.

The temperature-compensated dimensional
measuring device in accordance with the invention is
10   typically integrally packaged. It is easy to calibrate
and use, particularly because all temperature
sensing(s) typically transpire in a manner that is
preferably completely integrated with the dimensional
measurement process. The dimension and temperature
15   sensings, and the necessary calculations, are fully
automated and rapid. The device reads to the operator
much like a digital readout gauge, yet it is capable of
controllably displaying all parameters and sensed data
by which it derived the temperature-compensated
20   measurement.

The temperature-compensated dimensional
measuring device in accordance with the present
invention particularly enables predetermination of the
fit of workpiece components with accuracies that have
25   not been attainable previously without a significant
expenditure of time and manpower.

The present invention still further
contemplates a portable measuring device that indicates
the in-tolerance/out-of-tolerance condition of a
30   measurement made on a workpiece. The device includes
(i) a gauge for measuring the dimension of a workpiece,
(ii) a comparator for comparing the measured workpiece
dimension to a predetermined dimensional tolerance
range about a predetermined reference dimension, and
35   (iii) an indicator, responsive to the comparing of the

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comparison means, for indicating that, by results of
the comparing, the measured workpiece dimension is
either within or without the dimensional tolerance
range.

5   The dimensional tolerance range is preferably
variably predetermined, preferably by manual data
inputs to the device and more preferably by independent
manual input of both upper and lower limits of the
dimensional tolerance range.

10   Still further, the device permits variable
predetermination of a reference dimension, or that
dimension relative to which a measured dimension will
be determined to be either within, or without, a
dimensional tolerance range. The variable

15   predetermination of the reference dimension preferably
transpires merely by manually pressing a pushbutton
while the gauge is measuring a gauge block standard.
Thereafter the reference dimension will be the measured
dimension of the gauge block.

20   In the most sophisticated embodiments of the
device, a number of indicators are responsive to the
comparing for indicating that, by results of the
comparing, the measured workpiece dimension is either
within or without the tolerance range of dimensions

25   and, furthermore, if the measured workpiece dimension
is without the tolerance range, then it is either (i)
repairable so as to come within the range of dimensions
or (ii) unrepairable and subject to scrappage.

          The temperature-compensated measurement, and
30   the in-tolerance/out-of-tolerance indication, aspects
of the present invention can each be used separately.
However, both aspects are preferably used jointly in a
single device to perform quantitative dimensional
measurement that is both (i) temperature-compensated in

35   its accuracy, and (ii) user-friendly in identifying

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whether a particular measured workpiece dimension is either within, or without, a variably preset dimensional tolerance range.

In particular, a temperature-compensated, in-tolerance/out-of-tolerance indicating, quantitative measurement device in accordance with the present invention may be both calibrated on gauge blocks, and used to measure workpieces, that are not at a reference temperature. The device is quickly calibrated to a gauge block at any temperature because the temperature sensors within the device are themselves calibrated, and the device determines the temperature deviation of the gauge block from a reference temperature. From this determination the device is able to compute what the gauge block standard would measure should it be at the reference dimension, and this computed measurement becomes the reference measurement. A dimensional tolerance range, and a broader refurbishment/scrappage range, about this reference measurement may be quickly set. The device may then be used to perform temperature-compensated dimensional measurements of workpieces, displaying a true, temperature-compensated, quantitative dimensional measurement and indicating an in-tolerance/out-of-tolerance condition for each measured workpiece.

These and other aspects and attributes of the present invention will become increasingly clear upon reference to the following drawings and accompanying specification.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a diagrammatic view showing a first embodiment of a temperature-compensated quantitative dimensional measurement device in accordance with the present invention, particularly for measuring the

-side diameter of a workpiece.

FIGURE 2 is a diagrammatic view showing a second embodiment of the temperature-compensated quantitative dimensional measurement device in accordance with the present invention, particularly for measuring the inside diameter of a workpiece.

FIGURE 3 is a detailed view, partially in cross-section, showing a shoe assembly and a temperature sensor that are within the first embodiment of the temperature-compensated dimensional measuring device shown in Figure 1.

FIGURE 4 is a graph showing a typical variation of dimension with temperature due to a coefficient of expansion of four common steel workpieces, typically the axles of railroad cars.

FIGURE 5 is an electrical schematic showing a first embodiment of the electrical circuit which may be used within either, the first or the second, embodiment of the temperature-compensated dimensional measuring device in accordance with the present invention.

FIGURE 6 is a schematic block diagram showing a second embodiment of an electrical circuit which may be used within either, the first or the second, embodiment of the temperature-compensated dimensional measuring device in accordance with the present invention.

FIGURE 7, consisting of FIGURE 7a through FIGURE 7b, is a detail schematic diagram showing a variant of the second embodiment of an electrical circuit previously seen in schematic block diagram in Figure 6, which variant embodiment (i) indicates in-tolerance/out-of-tolerance conditions and (ii) accepts user specification of a tolerance range, as well as (iii) performing temperature compensation, within a measuring device in accordance with the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

A first embodiment of a temperature-compensated and tolerance-indicating quantitative dimensional measurement device in accordance with the present invention, particularly for measuring the outside diameter (OD) of a workpiece, is mechanically diagrammatically illustrated in Figure 1. All components of the first embodiment of the measuring device 10 are typically mounted to frame 11, but need not invariably be so mounted. The frame 11, typically made of metal and more typically aluminum, is in the shape of a "C" clamp. The frame 11 typically defines one or more lightening holes 12.

During use of the device 10 for measuring, the frame 11 is positioned about the outside diameter (OD) of workpiece 100. The frame 11 fixes shoes 13 and 14 in contact with the workpiece 100 at substantially one quadrant, or 90°, of separation along the circumference of the substantially cylindrical workpiece 100. The frame 11 also supports a third, moveable, shoe 15 in a position contacting the workpiece 100 at substantially 180° from fixed shoe 13. The 3 point suspension of frame 11 by its shoes 13-15 positioned against workpiece 100 constitutes the commonly recognized form of a three point snap gauge.

The shoe 13 is fixed to frame 11 during use of device 10 for measuring, but is adjustable relative to frame 11. The shoe adjustment assembly 16 includes micrometer 17. The micrometer 17 is manually rotated to force via a threaded shaft (not shown) the shoe 13 into greater or lesser extension from frame 11.

The shoe 14 is positionally constantly fixed to frame 11. The shoe 14 is but part of a positioning shoe and workpiece temperature sensor 18. The positioning shoe and workpiece temperature sensor 18,

which will be shown in detailed view in Figure 3,
detects the temperature of workpiece 100 at the
position of shoe 14 when the measuring device 10 is
operatively positioned thereabouts. An electrical
5   signal bearing information on this detected temperature
is electrically communicated (by a wire pathway not
shown in Figure 1) to computer 19.

The moveable measuring shoe 15 is moveable
relative to frame 11. It is mechanically connected to
10   size signal generator 20 which is affixed to frame 11.
The moveable measuring shoe 15 size and signal
generator 20 jointly constitute the dimensional
measuring assembly 21. The dimensional measuring
assembly 21 produces an electrical signal that bears
15   information on the displacement of moveable shoe 15 by
workpiece 100. This signal is received (by a wired
interconnection path not shown in Figure 1) at computer
19. The magnitude of the displacement of moveable shoe
19, and the informational content of the electrical
20   signal produced by dimensional measuring assembly 20,
is, of course, indicative of the size of workpiece 100
relative to frame 11. Accordingly, the dimensional
information produced by dimensional measuring assembly
21 is the outside diameter of workpiece 100 measured
25   relative to frame 11.

The frame temperature sensor 22 produces an
electrical signal that indicates the temperature of
frame 11. This signal is received (by a wired
interconnection path not shown in Figure 1) by computer
30   19.

In accordance with the present invention, the
computer 19 uses the measured workpiece dimension
information received from dimensional measuring
assembly 21 in combination with either or both of (i)
35   the workpiece temperature information received from

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positioning shoe and workpiece temperature sensor 18
and (ii) the frame temperature information received
from frame temperature sensor 22. The computer 19
computes a workpiece-temperature-compensated OD of
5   workpiece 100, a frame-temperature-compensated OD of
workpiece 100, or a workpiece- and frame-temperature-
compensated OD of workpiece 100.

The dimensional compensation resultant from the
temperature deviation of the workpiece 100, of the
10 frame 11, or of both the workpiece 100 and frame 11
from the predetermined reference temperature, nominally
59°F, is calculated in computer 19 from prior knowledge
of the predetermined thermal coefficient(s) of
expansion of the workpiece 100 and/or the frame 11.
15 Neither the temperatures nor the predetermined thermal
coefficients of expansion of workpiece 100 and frame 11
are necessarily equal. Indeed, the frame 11 and the
entire temperature-compensated measuring device 10 is
usually near room ambient temperature for having been
20 maintained in the (typically) indoor environment of
use. The workpiece 100 may, to the contrary, be at a
temperature significantly different from room ambient
temperature. Likewise, the frame 11 is typically
aluminum exhibiting a considerably different thermal
25 coefficient of expansion from the workpiece 100 which
is typically steel.

The temperature-compensated dimension
calculated by computer 19 is further communicated for
use, such as for use by a human operator or by a
30 machine control system. It is typically communicated
by a wired interconnection (not shown in Figure 1) to
display 23. The display 23, which is typically
digital, displays the temperature-compensated dimension
within a few seconds after the temperature-compensated
35 measuring device 10 has been placed in stable

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mechanical and thermal contact with the workpiece 100.
The computer 19 will not produce a display until sensed
dimensions and temperature have stabilized.

The first embodiment of the temperature-
5   compensated measuring device 10 in accordance with the
present invention is typically positioned into
mechanical and thermal contact with the workpiece 100
by being manually grasped about insulator 24 at the
location of hand hold 25. The insulator 24 serves to
10 diminish heat transfer from the human hand to the frame
11 during use of the measuring device 10 for
temperature-compensated measurements. A slow variation
in the temperature of frame 11 due to heating from the
hand or from any other source is not harmful,
15 especially in consideration of the compensation
preferably to be performed by the device 10 for any
thermally induced expansion or contraction of the frame
11. However, the insulator 24 primarily serves to
prevent that the frame 11, especially if it is small
20 and/or of low thermal mass and/or at a much different
temperature than the hand, should receive sufficient
heat transfer from the operator's hand so as to undergo
such a rapid change in temperature as would prevent the
temperature-compensated measurements of the device from
25 properly settling.

The mechanical and electrical interrelation-
ships and interconnections of the components of the
temperature-compensated measuring device 10 deserve
careful consideration. The dimension measured by
30 dimensional measuring assembly 21 is always relative to
frame 11. Therefore dimensional measuring assembly 21,
and the micrometer adjustment assembly 16 against which
dimensional measuring assembly 21 acts through
workpiece 100, must always be affixed to frame 11.

35

- 25 -

In accordance with the design of a three-shoe
snap gauge, a fixed shoe 14 will also be affixed to the
frame 11. However, it is not necessary that the
temperature sensing that is preferably done within the
5   shoe 14 as part of the positioning shoe and workpiece
temperature sensor assembly 18 must necessarily be
performed within such shoe 14, or that such temperature
sensing needs be performed at any fixed location
relative to frame 11 or device 10. Indeed, the
10   temperature sensing of the workpiece 100 could be
remote. The action of the preferred embodiment of the
temperature-compensated measuring device 10 that the
temperature sensing by positioning shoe and workpiece
temperature sensor 18 should inure naturally upon such
15   times as the device 10 is positioned about workpiece
100 for measuring the dimensions thereof is obviously a
beneficial feature of the present design.

It should further be understood that it is
properly the temperature of frame 11 that is being
20   sensed by frame temperature sensor 22, and that it is
principally the expansion or contraction of frame 11
that is being compensated for by computer 19. The
temperature of dimensional measuring assembly 21 is not
directly sensed, but is normally at the temperature of
25   frame 11. The dimensional measuring assembly 21, while
undergoing some small dimensional variation with
temperature, generally incurs a dimensional variation
with temperature that is so small relative to the
greater variation resultant from the greater dimension
30   of frame 11 so that this thermal variation of assembly
21 may be essentially neglected. Alternatively, it may
be considered that the temperature sensitivity of
dimensional measuring assembly 21 is incorporated into
a single coefficient of expansion factor that is
35   applied to both itself and frame 11 by computer 19.

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Both computer 19 and display 23 are shown in Figure 1 to be nominally affixed to frame 11. These components need not be, of course, integrally mounted to temperature-compensated measuring device 10. It is merely convenient that they should be so miniaturized and so mounted. In the preferred first embodiment illustrated in Figure 1 the entire temperature-compensated measuring device 10 is a unitary, self-contained, instrument.

A second preferred embodiment of the temperature-compensated measuring device in accordance with the present invention is shown in Figure 2, consisting of Figure 2a and Figure 2b. The temperature-compensated measuring device 30 is configured as a rocker gauge assembly having a substantially planar base 31 and a central handle 32. The handle 32 is grasped by the hand. Then dimensional measuring device 30 in the configuration of a rocker assembly is positioned within the bore of workpiece 101 so that the two fixed positioning feet 33 and the one moveable positioning foot 34 come into contact with the interior surface of the bore. Under the well understood principles of a rocker gauge assembly, the measuring device 30 is rocked from side to side in the bore of workpiece 101 until a minimum dimensional measurement is obtained.

Affixed to the base 31 and extending therefrom under the outwards force provided by spring 35 is a moveable temperature sensor 36. The temperature sensor 36 senses the temperature of the workpiece 101 at the interior of its bore. Meanwhile, another temperature sensor 37 senses the temperature of the base 31. Electrical signals from both temperature sensors 36 and 37 are routed (via pathways not shown in Figure 2a) to a computer 38. The computer 18 is typically located in

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an enlarged top to the handle 32. Also within the enlarged top to handle 32 is a display 39.

The positional movement of moveable foot 34 relative to base 31 incurred during rocking of

5   measuring device 30 within the bore of workpiece 101 produces an electrical signal output from dimensional measurement assembly 40. This signal output is indicative of the positional displacement of moveable foot 34, and consequently of the inside diameter (ID)

10   of the bore to workpiece 101. As with the first embodiment of the invention shown in Figure 1, the dimensional measurement assembly 40 measures dimensions relative to a frame, mainly base 31.

In accordance with the principles of the

15   present invention, the computer 38 is preprogrammed with the thermal coefficients of expansion of both base 31 and workpiece 101. The computer 38 uses the temperature reading of workpiece 101 that is derived from temperature sensor 36 and the dimension that is

20   derived from dimensional measurement assembly 40 in consideration of a predetermined thermal coefficient of expansion of workpiece 101 in order to derive a workpiece-temperature-compensated dimensional measurement.

25   The computer 38 preferably also uses the temperature of base 31 that is obtained from base temperature sensor 37 in conjunction with the same dimensional measurement of dimensional measurement assembly 40, and in further consideration of a

30   predetermined thermal coefficient of expansion of the base 31, to derive a base-temperature-compensated dimensional measurement. The computer 38 preferably derives a compensated temperature measurement that is both workpiece- and base-temperature-compensated. The

35   calculated temperature-compensated dimensional

measurements are typically displayed by computer 38
(via wired interconnection not shown in Figure 21) in
display 39.

An expanded view, partially in cross-section,
of the positioning shoe and workpiece temperature
sensor assembly 18 previously shown in Figure 1 is
shown in Figure 3. A support 51 is permanently affixed
to frame 11 (shown in Figure 1). The support 51
terminates in a widened lower base, or shoe, 52. The
face 53 to shoe 52 is contoured in a complementary
fashion to workpiece 100 in order to make good thermal
contact. The face 53 to shoe 53 is made from highly
thermally conductive material. It is typically made
from metal and more typically silver.

A temperature sensor 54, typically a
thermistor, is embedded within the typically silver
face 53 to shoe 52. Electrical connection to the
thermistor 54 is obtained via leads 55.

Backing the thermally conductive face 53 and
the thermistor 54 is a layer of thermal insulator 56.
At the region of the passage of leads 55 through shoe
52 the leads are protected by a grommet 57, typically
made of neoprene rubber, that is both thermally and
electrically insulating.

The preferred construction of the positioning
shoe and workpiece temperature sensor 18 provides that
the thermistor temperature sensor element will rapidly
attain the temperature of the workpiece 100 (shown in
Figure 1) into which it comes into thermal contact.
Meanwhile, the insulating layer 56 and the insulating
grommet 57 prevent heat from being transferred between
workpiece 100 and support 51 and frame 11 (shown in
Figure 1).

A conceptual analysis of the environment within
which the temperature-compensated measurement devices

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in accordance with the present invention suitably
function is aided by reference to the graph of Figure
4. The variation of dimension with temperature for
three typically workpieces, mainly three steel railroad

5   car axles, 101-104 is graphed in Figure 4. Because
each of the workpieces 101-104 is of the same steel
material, type 4340 by example, the slope of each curve
is identical. Because the material of the axle
workpieces 101-104 is homogenous, the plots are simple

10   straight lines. The slope of these lines is the
coefficient of expansion.

The suggested workpiece axle 101 is of minimum
acceptable size and passes through the point of
dimension 6.1905 inches at the reference temperature of

15   fifty-nine degrees Fahrenheit (59°F). Note that this
axle 101 also measures to be good, or usable, by an
uncompensated measurement taken at normal room
temperature 70-73°F.

The axle workpiece 102 is suggested to be

20   "perfect" in dimension, and exhibits a diameter of
6.1910 inches at the reference temperature of fifty-
nine degrees Fahrenheit (59°F), meaning that it is
precisely in the center of the acceptable range of axle
diameters. Note that this axle 102 erroneously

25   measures too large (but repairable) by uncompensated
measurement at high room temperature.

The axle 103 exhibits a maximum acceptable
diameter of 6.1915 inches at the same reference
temperature of fifty-nine degrees Fahrenheit (59°F).

30   Even though this axle 103 is acceptable and usable as
is, it is erroneously identified as oversize by
uncompensated dimensional measurement at room
temperature 70-73°F.

Finally, the axle 103 is repairable but

35   undersize. It measures, however, to be acceptable by

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uncompensated dimensional measurement at room temperature. To issue this axle for use will mean that its journal loosely fits a standard bearing, with high potential for early, possibly catastrophic, failure.

5   Further in accordance with the teaching of Figure 4, it is shown that each of the axles 101-104 exhibits a reduced dimension at temperature below the reference temperature. In fact, even the axle 102 which is "perfect" will appear to be outside the

10 acceptable dimensional range, i.e. of less than 6.1905 inches diameter, when it is measured at temperatures below approximately forty-five degrees Fahrenheit (45°F). Accordingly, the dimensional measurements actually performed on the axle workpieces 101-104 at

15 temperatures other than the reference temperature of fifty-nine degrees Fahrenheit (59°F) must be adjusted, or compensated, in order to correctly determine that diameter which each workpiece would assume should it have been elevated, and stabilized, to the reference

20 fifty-nine degree Fahrenheit (59°F) temperature.

The particular preferred algorithm in accordance with the method of the present invention for compensating for both the temperature of the workpiece and of the measuring gauge

25 is as follows.

A deviation from standard may be defined as:

$$G_{Std} - G_{Wkpc} + (T_{Std} - T_{Wkpc}) \times X_{Wkpc} - (T_{GStd} - T_{GWkpc}) \times X_{Gage}$$

The result of this calculation is greater than one (1) if workpiece is larger than standard. Within the

30 formula the expressions have the following meanings:

Std = Calibration standard sample of workpiece

Wkpc = the workpiece being measured

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G =   Dial Gage reading. The gage reading increases with increasing workpiece size.

G_{Std} = Gage reading on standard

G_{Wkpc} = Gage reading on workpiece

T_{Std} = Temperature reading on standard

T_{Wkpc} = Temp reading on workpiece

T_{GStd} = Temp reading of gage frame when measuring standard

T_{GWkpc} = Temp reading of gage frame when measuring workpiece

X_{Gage} =   amount of expansion per degree of gage frame (constant in the length and temperature units being used by the gage and temperature sensors).

X_{Wkpc} = amount of expansion per degree of workpiece material

     The coefficients of expansion and contraction for metals and mixtures are available in the CRC Handbook of Chemistry and Physics, 65th Edition, available from CRC Press Inc., Boca Raton, Florida. Coefficients particularly usable for metals common of employment in both frames of the dimensional measurement device and the workpieces upon which such devices operate are contained at pages D187-D188.

     Heat transfer rates of materials are likewise available in the same CRC Handbook of Chemistry and Physics, 65th Edition, at pages E11-E14. Such heat transfer rates are useful in calculating how long it takes the temperature sensors of the temperature-compensated measurement devices in accordance with the present invention to stabilize at a new temperature. These times represent programmed settling times, or time delays, during which the measurement device will not give an indication. Normally these times are only a few seconds. The measuring device in accordance with

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the present invention is fully self-protected by its programmed operation from attempting temperature-compensated measurement or temperatures that are changing "too fast", i.e., at rates that, in consideration of heat transfer rates, represent that substantial temperature stability has not been achieved. If temperatures of interest are not substantially stable then the measurement device will produce no indication rather than a confusingly wrong, or variable, indication.

First and second preferred embodiments of electrical circuits suitable for incorporation in the temperature-compensated measuring device in accordance with the present invention are respectively shown in schematic diagram in Figures 5 and 6. Each of the circuits is suitable for inclusion either within the first mechanical embodiment of the temperature-compensated measuring device shown in Figure 1, or within the second embodiment shown in Figures 2a and 2b. The first embodiment of the electrical circuit shown in Figure 5 uses a personal computer 190 as the computer 19 or 38 respectively shown in Figure 1 or Figure 2a. The second embodiment of the electrical circuit shown in Figure 6 uses a smaller microcontroller 380 as the computer 19 or 38 respectively shown in Figure 1 or Figure 2a.

Thus the first embodiment of the electrical circuit shown in Figure 5 may be considered relatively physically larger whereas the second embodiment of the electrical circuit shown in Figure 6 may be considered relatively physically smaller. If the first embodiment of the electrical circuit shown in Figure 5 is to be directly affixed to the frame 11 or base 31 that are respectively shown in Figure 1 or Figure 2a, then the measuring devices 10, 30 must be correspondingly large.

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It is not, however, necessary that the computers 19, 38 should be respectively physically mounted to the respective frame 11 and base 31. It is merely convenient that the computers 19, 38 should be so
5   mounted, and this mounting is best supported by the miniaturized embodiment of the electrical circuit shown in the schematic diagram of Figure 6.

In the first embodiment of the electrical circuit shown in Figure 5 the measuring assembly 21, 40
10   includes digital dial gauge 210, preferably Chicago dial type EDI-71 available from Chicago Dial Indicator Company, 1372 Rediker Road, DePlanes, Illinois 60016. The digital dial gauge 210 is connected to a dial gauge to RS232 interface 211. The interface 211 is
15   preferably type Fowler Gage Port available from Observational Systems, Inc., 15014 N.E. 40th, Suite 201-B, Redmond, Washington 98052. Other measuring assemblies 21,40 producing a digital signal output indicative of the measured dimension are known in the
20   industry, and will suffice within the temperature-compensated measuring devices of the present invention.

The signal output from interface 211 is received at an RS232C interface card 191 within personal computer 190. The information contained
25   within the signal is the measured dimension of the workpieces 100, 101 (shown in Figure 1 and Figure 2a).

The frame, or base, temperature sensors 22, 37 (shown in Figures 1, 2a) are preferably implemented as active semiconductor circuits based on semiconductor
30   temperature sensors. Such circuits and sensors have a rapid response time, and are highly sensitive to temperature variations. A resistor 220, nominally 10k ohms, is connected in series with semiconductor temperature sensor 221, nominally type LM335 available
35   from National Semiconductor, between voltage supply

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222, typically +12 volts dc, and ground 223. The signal derived at the junction of this voltage divider is received and amplified by operational amplifier 224. The amplified analog signal, indicative of the
5   temperature of the frame 11 or of base 31 (respectively shown in Figures 1, 2a) is received at analog to digital converter 192 within personal computer 190.

The frame, or base, temperature sensors 18, 36 are typically implemented as a thermistor 180. The
10 thermistor 180, typically type DC95 F502 W available from Thermometrics, 808 U.S. Highway 1, Edison, New Jersey 08817 has a wide operational temperature range. It is durable to shock, vibration, and high temperature gradients normally encountered during operational use.
15 Many additional commonly known thermistors are also suitable.

The thermistor 180 is within a constant current circuit of .1 milliamps established by constant current source 181. The constant current source 181 is powered
20 by supply voltage 182, typically +12 volts dc. The circuit between constant current source 181 and thermistor 180 is enabled to be closed by a signal driven from personal computer 190 to close analog switch 183. Analog switch 183 is typically one leg of
25 a CMOS switch type CD4066 (an industry standard part). The signal causing closing of the switch 183 is driven from the digital output lines circuit 193 within personal computer 190. When the switch 183 is enabled to be closed then the variable voltage developed across
30 the variable resistance of thermistor 180 by the constant current flow (.1 milliamps) therethrough is amplified in operational amplifier 184. The amplified signal is communicated to analog to digital interface 192 of personal computer 190. This signal bears
35 information on the temperature of the workpiece.

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From the received workpiece and frame (or base) temperatures, and in consideration of preprogrammed thermal coefficients of expansion as respectively besuit the material of the frame (or base) and the material of the workpiece, the personal computer 190 is able to calculate the workpiece- and frame (or base)-compensated-measurement of the workpieces 100, 101. The temperature-compensated dimensional measurement is displayed within display 230 of display and control 23, 39. The operator may cause the personal computer 190 to initiate a measurement cycle, alter the parameters of calculation, or perform other pertinent control via control area 231, typically a computer keyboard.

A listing in the BASIC language of a computer program particularly suitable for workpiece- and gauge-temperature-compensated measurement of a railroad axle is attached to the present specification as Appendix A. Preprogrammed constants include the following.

ThermCurrent = 0.1 milliamperes is the current of the thermistor thermally communicating with the workpiece.

ThermTDev = 1 is the maximum allowable deviation in degrees for a "stable" reading.

StableNReq = 5 is the length of time required in seconds for the measurement device to stabilize.

HandleFactor = 0.0005 inches per degree to add to reading, meaning the coefficient of expansion times the length of the gauge frame, per degree Fahrenheit.

AxleFactor = -0.000225 inches per degree to add to the dimensional reading, meaning the coefficient of expansion times the axle diameter, per degree Fahrenheit.

All these constants are obviously subject to
predetermination as besuits the particular temperature-
compensated measurement problem at hand.

5
The second embodiment of an electrical circuit
suitable for use within either embodiment of the
temperature-compensated measuring devices 10, 30 in
accordance with the present invention is shown in
Figure 6. This circuit operates similarly to the
embodiment of Figure 5. The dimensional measuring
10
assembly 21, 40 typically consists of displacement
gauge 400 connected to a linearizing interface 401.
The gauge 400 and linearizing interface 401 are both
available from Technetics, Inc., 481 Cypress Lane, El
Cajon, California 92020. Unlike the digital dial gauge
15
210 and its accompanying dial gauge to RS232C interface
211 that were within the first embodiment of the
electrical circuit shown in Figure 5, the signal output
of the linearizing interface 401 is analog, and not
digital. This signal output is received within an
20
analog to digital converter 381 that is integral to
microcontroller 380. The microcontroller 380 is
preferably type 68705 or 68HC11 available from
Motorola, Inc.

The frame temperature sensor 22, 37 is again
25
based on a semiconductor temperature sensor 221 type
LM335. The operational amplifier 224 that was shown in
Figure 5 is not necessary for amplification of the
electrical signal derived from sensor 221 during the
signal transmission to microcontroller 380 because the
30
microcontroller 380 is normally located physically
proximate to the frame (or base) temperature sensors
22, 37.

The workpiece temperature sensor 18, 36,
consist of the identical components 180-184 as were
35
present within such workpiece temperature sensor within

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the first embodiment of the electrical circuit shown in
Figure 5. The signal output controlling the CMOS
analog switch 183 is now derived from the parallel I/O
section 382 of microcontroller 380. The
microcontroller 380 additionally contains central
processing unit section CPU 383, erasable random access
memory section RAM 384, and permanent random access
memory section ROM 385.

In consideration of preprogrammed information
regarding the thermal coefficients of expansion of both
the frame (or base) 11, 31 and the workpieces 100, 101
(shown in Figures 1, 2a), and in further knowledge of
the workpiece dimension and the frame and workpiece
temperatures, the microcontroller 380 calculates the
frame- and workpiece-compensated dimensional
measurement. This measurement is transferred via
parallel I/O 386 to display and control section 23, 39.

Within the miniaturized embodiment of the
electrical circuit shown in Figure 6, the display 230
preferably consists both of LCD indicators that are
typically used for numerical display and of LED
indicators that are typically used for display of the
operational status of the temperature-compensated
measuring device. The control of the temperature-
measuring devices 10, 30 is preferably enabled through
simple operator switches 231.

In operational calibration and use, the
temperature-compensated measuring devices in accordance
with the present invention exhibit considerable
flexibility. That a measuring instrument should be
calibratable, and calibrated, by such means as the
micrometric adjustment assembly 16 shown in Figure 1,
is not new in the art. The temperature-compensated
measuring devices 10, 30 in accordance with the present
invention readily support zeroing or calibration

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relative to a reference dimensional standard by both
mechanical means and by operator-initiated
normalization, or zeroing, of the indicated dimension.

5   An initial, factory, calibration of a
temperature-compensated measuring device 10, 30 is
undertaken when its frame (or base) 11, 31 is at the
59° reference temperature and the instrument is
dimensionally measuring a dimensional standard
workpiece 100, 101, or Jo block. The measurement(s) of
10   such dimensional standards are normally traceable to
the U.S. National Bureau of Standards, or equivalent
foreign authority. Then, while the dimensional
measuring instrument is still calibrated, two graphical
plots are obtained. A first plot is the change in the
15   absolute measurement of the measuring devices 10, 30
when the temperature of such devices is changed while
the temperature of the Jo Block remains fixed at 59°F.
The slope of such a curve is typically only the
coefficient of expansion of the frame, or base, 11, 31.
20   A second plot of the measuring devices 10, 30
measurements is obtained while the measuring devices
10, 30 remain calibrated at the 59°F temperature while
the Jo block varies in temperature. This variation
with temperature exhibited by the Jo block is typically
25   not the same variation as will ultimately be exhibited
by the workpiece, being that the Jo block and the
workpiece are not required to be made of identical
material, and are normally made of different materials.

     After deriving the two plots, it is possible to
30   calibrate the temperature-compensated dimensional
measuring devices 10, 30 in accordance with the present
invention to the original calibration Jo blocks when
either (i) the temperature-compensated measuring
device, (ii) the Jo block, or (iii) both the
35   temperature-compensated measuring device and the Jo

block are not at the reference 59°F temperature. This
calibration flexibility is extremely valuable. For
example, a temperature-compensated measuring device in
accordance with the present invention may typically be

5   switch controlled to indicate its own sensed
temperature, the sensed temperature of the workpiece Jo
block, or the uncompensated measurement that it
currently senses. Suppose it is known from the
calibration curves that a Jo block of diameter 6.0004

10   inches at 59°F will measure 6.0011 inches at 70°F.
Suppose that it is also known that a temperature-
compensated measuring device 10, 30 that is zeroed to
read the 59°F Jo block to be 6.0004 inches when the
measuring device 10, 30 is at the same 59°F temperature

15   will measure the same 59°F Jo block to be 5.9996 inches
when the frame (or base) 11, 31 of the measuring device
10, 30 is at 73°.

        Consider now the calibration procedure for a
temperature-compensated measuring device when its own

20   sensors indicate that a Jo block is at 70°F and that
its own frame is at 73°F. The temperature of the Jo
block indicates that the correct reading should be
.0007 inches high, whereas the temperature of the frame
(or base) indicates that the reading should be .0008

25   inches low. The net of these two pieces of information
is that a 73°F temperature-compensated measuring device
measuring a 70°F Jo block (which Jo block is 6.0004
inches at 59°F) should read, if calibrated, 6.0005
inches. Suppose then, upon a singular instance, the

30   temperature-compensated measuring device 10, 30 in
accordance with the present invention shows an
uncompensated dimensional measurement of the Jo block
equaling 6.0006 inches. This reading is too high by
.0001 inches. The device is correspondingly manually

35   calibrated, either by mechanical adjustment or by input

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of parameters to the computer processor, to subtract
.0001 inches from the workpiece Jo block measurement
that it senses. The device 10, 30 thusly thinks that
it sees, and displays as the uncompensated measurement,
a dimension of 6.005 inches for a 70°F Jo block and a
73°F frame. From this uncompensated measurement the
device will derive a workpiece- and self-temperature
compensated measurement of 6.0004 inches -- which is
the true Jo block measurement.

The temperature-compensated dimensional
measuring device was calibrated without necessity of
having adjusted either its own temperature, or the
temperature of the Jo block, to the reference
temperature of 59°F. This flexible calibration
obviously saves time and permits a frequent
recalibration in the work environment.

The present invention is also directed to
conveniently displaying in-tolerance/out-of-tolerance
determinations made responsive to quantitative
dimensional measurements, as well as the quantitative
dimensional measurement themselves. The dimensional
measurements for which the in-tolerance/out-of-
tolerance determinations are made are preferably
temperature-compensated measurements in accordance with
the present invention, but need not be so.

A detail schematic diagram, showing the second
embodiment of an electrical circuit previously seen in
the schematic block diagram of Figure 6, is shown in
Figure 7, consisting of Figure 7a through Figure 7d, in
order that the operator switches 231, and the display
230, may be shown with greater particularity. The
variant embodiment schematically diagrammed in Figure 7
is different from the embodiment schematically block
diagrammed in Figure 6 primarily for using a
MICROCONTROLLER 3800 that is of Type 68HC805C4, and

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which correspondingly does not have an included analog
to digital converter. Instead, the analog-digital
converter 382 which was within the microcontroller 380
shown in Figure 6 is instead a separate component, A/D
5   CONVERTER 3820 shown in Figure 7. There is no
essential difference between the embodiments
schematically diagrammed in Figure 6 and Figure 7 and
their accompanying firmware control program as regard
their ability to temperature compensate dimensional
10   measurement, and to both quantitatively and
qualitatively (in-tolerance/out-of-tolerance) display
the results thereof.

        Referring to Figure 7, the dimensional
measuring assembly again consists of displacement gauge
15   400, preferably a linear variable displacement
transducer (LVDT), normally type 0272-000 commercially
available from Trans-Tech Corporation. The
displacement signal developed in the LVDT displacement
gauge 400 is received at linearizing interface and LVDT
20   signal conditioner 401, circuit type NE 5521N available
from Signetics Corporation. The linearized and
condition signal output from linearizing interface 401
is routed through operational amplifier 403, typically
one of four CMOS operational amplifiers type LMC 660XX
25   available from National Semiconductor Corporation, to
be received at 10 bit A/D CONVERTER 3820, typically
type CDP68HC68AZ available from CMOS Peripherals, Inc.

        Continuing in Figure 7, the FRAME TEMPERATURE
SENSOR 22, 37, is, as previously shown in Figure 6,
30   again preferably based on part no. LM 335 available
from National Semiconductor Corporation. The analog
signal output of the sensor is amplified in operational
amplifier 224, another part of the CMOS quad
operational amplifier part no. LMC 660XX available from
35   National Semiconductor Corporation, and received is

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into A/D CONVERTER 3820.

      The WORKPIECE TEMPERATURE SENSOR 18, 36, is
likewise again preferably based on a temperature
transducer, preferably part no. AD 590 available from
5   Analog Devices. The signal output of this WORKPIECE
TEMPERATURE SENSOR 18, 36 is amplified in operational
amplifier 184, still another quarter of the CMOS quad
operational amplifier NSC part no. LMC 660XX, and
received into A/D CONVERTER 3820. The WORKPIECE
10   TEMPERATURE SENSOR 18,36 contains a switch 1830 that
activates the sensor 180 from voltage supply V_{unREG} only
when it is properly contacting the workpiece, normally
by being pressed tightly against an axle. As such the
operation of switch 1830 differs slightly from the
15   operation of switch 183 that was previously shown in
Figure 6, and that was explained in conjunction
therewith.

      The unregulated battery voltage VunREG and the
reference voltage +2.5 Vref are also received into A/D
20   CONVERTER 3820 as voltages indicative of the battery,
and regulated, power of the dimensional measuring
assembly.

      The MICROCONTROLLER 3800, typically 8 bit type
MC68HC805C4 available from Motorola, Inc., operates in
25   accordance with a firmware program stored in EEPROM
386, preferably type no. 93C46 available from
International CMOS Technologies, Inc. In accordance
with its programmed operations, the MICROCONTROLLER
3800 causes the A/D CONVERTER 3820 to select among the
30   various analog signals that it receives, and in turn
receives the digital data from A/D CONVERTER 3820 that
is indicative of the selected informational quantity.
The MICROCONTROLLER 3800 runs the algorithm, previously
explained, by which the dimensional measurement
35   ultimately derived from LVDT displacement gauge 400 is

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compensated for both the temperature of the workpiece and the temperature of the gauge.

In addition to its temperature compensation function, the MICROCONTROLLER 3800 is operative, under firmware program control, to both receive control from manual pushbutton switches 231, and to produce both (i) quantitative displays and (ii) go/no-go indications in the form of indicator lights. Manual actuations of the switches 1 through 4, SW1 through SW4, of the operator switches 231 are received directly at MICROCONTROLLER 3800. These switches SW1-SW4 are labeled, and their actuations respectively indicate, an input of "+", "-", "REFERENCE", and "SET LIMITS" to the MICROCONTROLLER 3800. The meaning of these particular inputs will be explained shortly during discussion of the functional performance of the in-tolerance/out-of-tolerance indicating device in accordance with the present invention operating under control of MICROCONTROLLER 3800.

A final one of the operator switches 231, switch SW5 for "ON/OFF", connects through a level converter and switch debouncer circuit to selectively enable or disable adjustable voltage regulator and power supply circuit 700, type LM 317L available from National Semiconductor Corporation, and associated components. The adjustable regulator and power supply 700 produces the +5 v.d.c. power that is used by all electronics. The fundamental power is provided by pluggable battery BT1, typically 7.2 v.d.c. Actuation of the "on/off" switch SW5 also acts in NAND Schmitt Triggers 701, 702, 703, typically types MC 14093B available from Motorola, Inc., to, after a two second power switch detection delay, produce a power-on reset signal that will, save that circuit operation be inhibited by the presence of low voltage, serve to

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reset the MICROCONTROLLER 3800.

Continuing in Figure 7, the firmware program operated by MICROCONTROLLER 3800 produces, as a first portion of display 230, an alphanumeric liquid crystal digital display LCD 2307, type LC 5/3041-300.XX/XX available from Amperex, as driven by LCD driver 2302, type MM5453 available from National Semiconductor. The alphanumeric information displayed by LCD 2301 is the quantitative dimensional measurements, and, at alternative times, messages to the device operator.

Of particular importance to the present invention, the firmware program operated within MICROCONTROLLER 3800 also causes, within the display 230, selected ones of light emitting diode indicators DS1-DS4 to illuminate. The LED DS1 is typically green, and is labeled and indicates "OK". Similarly, the LED DS2 is typically yellow and is labeled "REFURB", meaning that refurbishment is possible. The LED DS3 is typically red, and is labeled "SCRAP", meaning that refurbishment is not possible and that scrappage of the measured workpiece is indicated. Finally, LED DS4 is typically green, and is labeled "TEMP MEASURE". The illumination of this LED indicator DS4 means that the device is performing temperature measurements, and is waiting for a predetermined period to (potentially) allow such measurements to stabilize (if necessary).

In general within the schematic diagram of Figure 7, all resistors are 1%, 1/4 watt, unless otherwise noted. The indicated capacitor values are in microfarads, unless otherwise noted. Preferred component types and values are as follows:

Resistors (1%, 1/4 watt), 47 qty:

R1	10M	R16	10K	R31	2K ADJ	R46	10K	R61	18K
R2	—	R17	5.1K	R32	—	R47	5K	R62	20K ADJ
R3	—	R18	—	R33	10K	R48	10K	R63	1K
R4	—	R19	1M	R34	270K	R49	100K	R64	100
R5	—	R20	30(1W)	R35	50K ADJ	R50	10K	R65	10K
R6	—	R21	—	R36	10K	R51	10K		
R7	—	R22	—	R37	—	R52	10K		
R8	—	R23	20K	R38	20K	R53	576	RP1	330
R9	—	R24	120K	R39	10K	R54	1.74K	RP2	10K
R10	1K	R25	120K	R40	100K	R55	12.7K		
R11	—	R26	20K ADJ	R41	20K	R56	2K ADJ		
R12	—	R27	100K	R42	20K	R57	—		
R13	10K	R28	270K	R43	20K	R58	—		
R14		R29	50K ADJ	R44	1M	R59	5K		
R15	10K	R30	8.2K	R45	1M	R60	1K		

Capacitors (in microfarads), 14 qty:

C1&2	20 pF	C9	120 pF
C3	0.1	C10	
C4	470 pF	C11	.47
C5	20	C12	.0041
C6	100	C13&15	1.0
C7	.01	C14	.002
C8	2.0		

Diodes, 7 qty:

D4	in 34K
D5	
D6	
D8	in 4148
D9	
D10	
D7	4v zener

Transistors, 4 qty:

Q1	MPS6515
Q2	
Q3	MPS 6523
Q4	

The voltages produced by the two temperature
sensors are scaled so that each deviation of 1°K or C
temperature output from A/D CONVERTER 3820 is equal
to -30 mV. The temperature voltages are balanced so

5   that a temperature of 250°K = -23°C produces a signal
output of 2.5 v.d.c. Meanwhile, a temperature reading
of -13°C produces an equivalent signal output of 2.2
v.d.c., a temperature of 0°C produces a signal output
of 1.81 v.d.c., and a temperature of 60.3°C produces a

10   signal output of 0 v.d.c.

The LVDT sensor of the displacement gauge 400
is also scaled to the A/D CONVERTER 3820, and thus to
the MICROCONTROLLER 3800. This scaling is accomplished
under control of the firmware program resident with the

15   EEPROM 386 and executed by MICROCONTROLLER 3800. The
scaling of the LVDT of the displacement gauge 400 is
factory preset to cover a range of -25.6 to +25.5 mils;
-12.8 to +12.7 mils; or -6.4 to +6.3 mils. The preset
range to which the LVDT is scaled is obviously a

20   function of the deviation to be expected in the
workpieces which are being quantitatively dimensionally
measured.

The device in accordance with the present
invention may be used, for example, for quantitatively

25   measuring railroad axles, and for classifying them in
accordance with their measurements into acceptable,
refurbishable, and scrap categories. As such, the
device functions equivalently to a conventional snap
gauge. However, one advantage of the device in

30   accordance with the present invention is that it also
takes into account temperature, and hence may be used
to measure axles without requiring that they be brought
to a known reference temperature. A further advantage
of the device in accordance with the present invention

35   is that it directly indicates whether a measurement is

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within, or without, a measurement tolerance range,
simplifying determinations when the device is used by
unskilled or inattentive personnel, and reducing error.

5   In normal use an On/Off button is pushed to
switch the device on. The same On/Off button is pushed
to turn the device off. Alternatively, the device will
switch itself off if it is not used to measure anything
for a time duration longer than approximately one
minute.

10   In normal use, the operator is concerned with
two main modes of operation. One of these modes is the
"Reference" mode. In this mode a reference axle is
measured in order to define the gauge's "zero" point.
After taking this reference, the gauge reverts to its
15   normal, "Measure", mode that is used for measuring test
axles.

There are two other modes which are used
infrequently. A "Parameter Mode" is used to set
certain limits and constants, such as the ranges for
20   Accept/Refurbish/Scrap, and so on. A "Diagnostic Mode"
is used if it is necessary to test the gauge itself.

When first switched on, the device in
accordance with the present invention assumes that it
will be measuring a workpiece, and compares the
25   workpiece measurement to the reference measurement.
Whenever a reference is measured then that measurement
is remembered, even if the instrument is subsequently
switched off.

The device contains a switch which allows it to
30   detect when the temperature measuring foot (the middle
foot) is properly contacting the axle. If the device
is not properly engaged then three things happen: The
"axle engaged" light will not be lit, the numeric
display reads an uncompensated displacement (which is
35   usually not a useful figure), and the three OK/REFURB/

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SCRAP lights will not operate.

In this case, all that is necessary is to move the device into the proper position on the axle with slight pressure, and the "TEMP MEASURE" light will
5 illuminate to confirm proper seating.

To measure a reference in reference mode the device is first positioned on a standard reference gauge block so that the "TEMP MEASURE" light comes on. The "Ref" key is then pressed. The display will read
10 "rEF". When ready, the operator presses the Ref button again. The display now alternates between "hold" and a count showing approximate seconds remaining until the device considers the temperature to be stable.

When the reference measurement is locked in,
15 the device automatically reverts to "Measure" mode, and will initially indicate 000.0 mils +/-0.1. This, of course, indicates that the reference gauge block is the same size as itself.

The time required to stabilize is a function of
20 a given workpiece, and is empirically determined. As will shortly be discussed, this stabilization time can be manually entered into the device.

To measure a workpiece in "Measure" mode the device is simply turned on. The device will start in
25 the "Measure" mode, and will revert to this mode after measuring a reference gauge block. In other words, the "Measure" mode might be considered "normal" mode. In order to measure a workpiece such as an axle, the device is placed on the test axle so that the "TEMP
30 MEASURE" light comes on.

The device may indicate the measurement immediately, and activate one of the OK/REFURB/SCRAP lights. However, if the axle temperature is substantially different from whatever the device was
35 previously touching, there will be a short wait while

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the temperature is measured. During this waiting period the display will flash between the present reading and a number indicating minimum seconds remaining before the temperature reading will be stable enough to judge the OK/REFURB/SCRAP condition.

If the device is repositioned within a short time of a measurement then it will continue to measure smoothly. However, if it is removed from the axle for a longer period, when it is remounted it will wait to ensure that the temperature measurement is stable. This "Repeat-Measure-OK" time period is preset to 5 seconds, but it is one of the adjustable parameters which can be changed if desired.

There are a number of parameters in the device that may be set up or adjusted. These are described in the list below. The procedure for setting a parameter involves two steps; first select the parameter, then increase or decrease the value.

To start set parameters, the following procedure is followed. With the device already switched on the SET LIMITS key is pressed. The display will read "P" followed by a parameter number. this number can be increased or decreased to select the desired parameter number by using the + and - keys. The "SET LIMITS" key is then depressed again to actually select the particular parameter that is desired to be modified.

The parameters are shown in Table 1, below. The present value of the parameter will be shown. This value can be increased or decreased with the "+" and "-" keys. To finish setting a parameter, the "SET LIMITS" key is pressed. The device returns the P-number display, allowing the operator to select another parameter by repeating previous steps. To finish setting parameters altogether, the "REFERENCE" key is

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pressed one last time. This returns the device to
normal "Measure" Mode.

Table 1. Device Adjustable Parameters

Parameter #	Parameter Meaning
0	Maximum temp fluctuation allowed in temperature-stable wait period, from 0.1 °C to 10°C.
1	"Good" grade maximum positive tolerance, 0.0 to 10 mil. (d_{UprTol})
2	"Good" grade maximum negative tolerance, -0.0 to -10 mil. (d_{LvrTol})
3	"Refurb" grade maximum positive tolerance, 0.0 to 10 mil. (d_{UprRfb})
3	"Refurb" grade maximum negative tolerance, -0.0 to -10 mil. (d_{LvrRfb})
5	Low battery trigger point (this is in A/D counts).
6	Handle temperature coefficient (in units of 0.1 micro-inch/°C, range 1024 to 2047)
7	Axle temperature coefficient (in units of 0.1 micro-inch/°C, range 512 to 1023)
8	Minimum wait for temperature stablization, in seconds, 2 corresponds to 1 second, 3 is 2 seconds, and so on.
9	Displacement sensor range, 0 means -25.6 to +25.5 mil 1 means -12.8 to +12.7 mil 2 means -6.4 to +6.3 mil. This is a factory adjustment since it requires a corresponding change of the internal circuitry.
10	English/Metric readout. 0 means English (mils), 1 means metric (mm). Note that this changes only the readout. The parameters must still be entered in the units shown in this table. The "Measure Mode" the present units are indicated by the position of the decimal point.
11	Repeat-Measure-OK timer period. (Factory set to 5 secs)

A function is included to reset all parameters
to "factory" values. This function is useful if the
parameters get to a disorderly state as a result of too
much manipulation. It may then be easier to reset the
parameters to the "factory" presets, rather than adjust
them all individually. To do this, the "SET LIMITS"
key is held down while the device is turned on.

Under rare circumstances the device may forget
its settings. If this happens when the device is
powered-on then the display will read "Err". The

device must be turned off and switched on again while
holding down the "SET LIMITS" key at the same time.
This will reset the parameters to the factory values.
It is necessary to then reset any parameters which are
5   desired to be set to other than factory values (see the
Parameter-Setting procedure).

        The device also supports a number of diagnostic
functions. These functions are handy for verifying
that independent parts of the device are working. To
10   enter "Diagnostic" mode the following procedure is
followed. The device is turned off. The "REFERENCE"
key is held down. The "On" key is then pressed and
released. The "REFERENCE" key is continually held
until the display reads "Sel". The "+" or "-" keys are
15   then depressed to advance to the code of interest. The
possible choices are shown in the following Table 2.

<div align="center">

Table 2. Diagnostic Modes

Displacement	Display Reads
Axle temp	AXLe AHLE
Handle temp	hAnd
Battery	bAtt
Displacement	dISP

</div>

25   When the desired function is reached then the "SET
LIMITS" key is pushed.

        The Axle (workpiece) and Handle (device)
temperature diagnostic mode shows a readout in degrees
C. In fact, the indicated temperature is only accurate
30   to about 3 to 5 degrees, although the changes in
temperature (which is what the device is interested in)
are registered to about +/-.2 degrees.

        The displacement diagnostic mode shows the raw
dimensional measurement from the displacement sensor.
35   This is actually identical to the readout when the
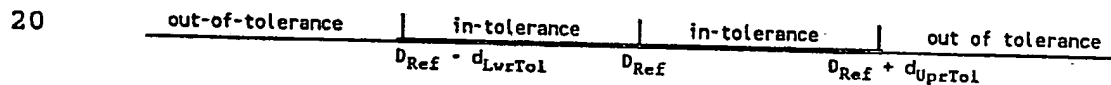"TEMP MEASURE" light is not on.

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The Battery diagnostic mode shows the raw A/D count for the battery voltage.

To quit the diagnostics the device is turned off, and started again.

Considering the overall operation of the device in accordance with the present invention in mathematical terms, the reference dimension is variably predetermined to be D_{Ref} by placing the instrument on a dimensional standard. An upper tolerance limit above D_{Ref}, or d_{UprTol}, and a lower tolerance limit below D_{Ref}, or d_{LvrTol}, are manually specified. An actual dimensional measurement D_{Actual} of workpiece is within tolerance if:

$$D_{Ref} - d_{LvrTol} \leq D_{Actual} \leq D_{Ref} + d_{UprTol}$$

Represented on a scale line, this relationship is

out-of-tolerance	in-tolerance	in-tolerance	out of tolerance
	$D_{Ref} - d_{LvrTol}$	D_{Ref}	$D_{Ref} + d_{UprTol}$

when the in-tolerance region is diagrammatically represented in double line.

Furthermore, a refurbishment, or repair, tolerance is preferably also manually specifiable. Both a lower refurbishment tolerance, d_{UprRfb}, and an upper refurbishment tolerance, d_{UprRfb}, are preferably individually specifiable. The refurbishment tolerances are broader than the regular, acceptance tolerances, i.e.:

$$d_{LvrRfb} \geq d_{LvrTol}$$
$$d_{UprRfb} \geq d_{UprTol}$$

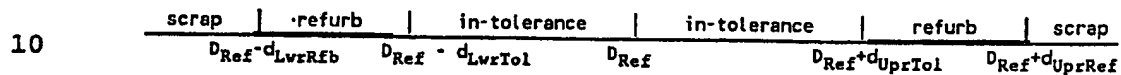An actual dimensional measurement D_{Actual} of a workpiece is within refurbishment range if:

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$$D_{Ref} - d_{LwrRfb} \leq D_{Actual} < D_{Ref} - d_{LwrTol}$$

or

$$D_{Ref} + d_{UprTol} < D_{Actual} \leq D_{Ref} + d_{UprRfb}$$

Represented as a scale line, this relationship is as follows:

scrap	refurb	in-tolerance	in-tolerance	refurb	scrap
$D_{Ref}-d_{LwrRfb}$	$D_{Ref}-d_{LwrTol}$	D_{Ref}		$D_{Ref}+d_{UprTol}$	$D_{Ref}+d_{UprRef}$

when the refurbishment regions are diagrammatically represented in double line.

In accordance with the present invention, the dimensional measurements D_{Ref} and D_{Actual} are each temperature compensated. In mathematical terms:

$$D_{Ref} = G_{Std} + (T_{Ref} - T_{Std}) \times X_{Std}$$
$$- (T_{Ref} - T_{GStd}) \times X_{Gage}$$

where the expressions have the same meaning as before with T_{Ref} being the predetermined reference temperature, for example 59°, and X_{Std} being the amount of expansion per degree of the material of the gauge block standard. It may thusly be noted that the reference dimension, D_{Ref}, to which the actual dimension, D_{Actual}, will be compared is itself temperature-compensated. Accordingly, it is not necessary to calibrate the device of the present invention to a gauge block reference standard that is at a predetermined reference temperature, but only to such a gauge block reference standard at any convenient temperature.

Similarly, the workpiece dimensional measurement is expressed as:

$$D_{Actual} = G_{Wkpc} + (T_{Std} - T_{Wkpc}) \times X_{Wkpc}$$
$$- (T_{GStd} - T_{GWkpc}) \times X_{Gage}$$

where the terms have the same meaning as before.

In accordance with the preceding discussion, it should be recognized that many alterations and

adaptations of the temperature-compensated measuring
devices in accordance with the present invention are
possible. If dimensional sensitivity of the workpiece
to variations in temperature is not particularly acute,

5   and/or is accommodated by other means than temperature
compensation of dimensional measurements, then it would
be possible to operate the device in accordance with
the present invention to compensate only for its own
frame (or base) temperature. Conversely, if the

10   temperature-compensated dimensional measuring devices
in accordance with the present invention are
dimensionally so small that their own dimensional
variations with temperature are inconsequential, and/or
are made out of materials that are highly dimensionally

15   stable with temperature variation, and/or are always
operated at an identical temperature, then these
devices could be used to compensate only for the
temperature of the workpiece and not additionally, as
is preferable, for the temperature measurement of the

20   devices themselves.

        As well as the possibility of using the devices
of the present invention by parts in a reduction of
their preferred capacity, it is obviously possible,
once a flexible computational computer is employed, to

25   extend to still other factors the temperature
compensation that is employed in accordance with the
principles of the present invention. Particularly,
compensation for variations with temperature might be
employed for more than just the frame (or base), 11, 31

30   and the workpieces 100, 101. This additional
compensation might relate to second order effects, or
to the non linearities within the temperature-measuring
devices themselves. The computers might be employed
not merely to perform calculations as besuit

35   substantially linear coefficients of expansion, but to

match indicated temperatures and dimensional
measurements against predetermined mappings in order to
calculate a best fit of observed conditions to prior
data in order to determine true dimensions.

5   The present invention is also suitable for
incorporation within a closed loop control system
during machining or other processing operations wherein
processing operations are controlled in consideration
of workpiece dimension, machine head position, or like
10   dimensional measurements. It will be understood that
the compensation performed by the present invention is,
under computer control, substantially continuous. The
continuous compensation can account for continuing
variations in any of the dimension or the temperature
15   of the workpiece, or the temperature of the measuring
device.

           This suitable expansion of the present
invention deserves careful deliberation. For example,
when a workpiece is being turned on a lathe the heat
20   generated in the turning process flows in both
directions from the cutting tool. The heat which goes
toward the already formed part is of no consequence
(other than it may act as a thermal barrier to the heat
being generated by the cutting tip). The heat
25   contained within the removed shavings is likewise of no
consequence. The heat transferred toward the uncut
section is of concern because it is expanding the part
dimensionally. The cutting tip typically moves
parallel to the centerline of the machine. Because of
30   its thermal expansion the part is cut on a taper which
is more pronounced the closer to the end of the cut.
The reason for this is because the transfer of heat
from the metal to the air at the end of the part is
significantly slower than internal heat transfer in the
35   metal. If the sensing and compensation in accordance

with the present invention are used to move the cutting
tool so as to compensate for the heat changes in the
material being formed then the end product may be made
significantly more dimensionally accurate. In many
5   cases this increase in accuracy would eliminate any
requirement(s) for secondary processing. Therefore the
expansion of the present invention into active process
control systems is contemplated.

In sensing the dimension or temperature of the
10 workpiece it should be understood that such sensing
need not be by direct physical contact. Even if the
dimension of a workpiece were to be measured relative
to a frame by a non-contact method such as reflected
light, then the temperature variations of the workpiece
15 could still be pertinent to the determination of the
workpiece true dimension. The temperature of a
workpiece may be determined by sensing the infrared
radiation emissions therefrom, and need not exclusively
be determined by physical contact with the workpiece.
20   In consideration of these and other possible
adaptations and modifications of the present invention,
the present invention should be interpreted in
accordance with the scope of the following claims,
only, and not solely in accordance with those preferred
25 embodiments within which the invention has been taught.

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CLAIMS

1.   A workpiece-temperature-compensated
quantitative dimensional measuring device comprising:
5   gage means for quantitatively measuring a
quantitative dimension of an arbitrarily-sized
workpiece;
                     first thermal sensing means, held by the
gage means in thermal communication with the workpiece,
10   for measuring a first temperature of T_{Wkpc} of the
workpiece; and
                     computational means for receiving the
quantitative dimension measurement G_{Wkpc} from the gage
means and the first temperature measurement T_{Wkpc} from
15   the first thermal sensing means and for producing, in
consideration of a predetermined first dimensional
sensitivity X_{Wkpc} of the workpiece to temperature
variations about a first predetermined reference
temperature T_{Std}, that temperature-normalized
20   quantitative dimension $G_{Wkpc} + (T_{Std} - T_{Wkpc}) \times X_{Wkpc}$ that
the workpiece would measure to and by the selfsame gage
means upon such times as the workpiece was to be at the
first predetermined reference temperature T_{Std}.
      2.   The workpiece-temperature-compensated
25   quantitative dimensional measuring device according to
claim 1 further adopted for compensating for its own
dimensional self-variation with temperature, the
workpiece- and self-temperature compensated dimensional
measuring device according to claim 1 further
30   comprising:
                     second thermal sensing means in thermal
communication with the gage means for measuring a
second temperature T_{Gwkpc} of the gage means; and
                     wherein the computational means is further
35   for receiving the second temperature measurement T_{Gwkpc}

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from the second thermal sensing means and for
producing, in further consideration of a predetermined
second dimensional sensitivity X_{Gage} of the gage means to
variations in its temperature about the a second

5   predetermined reference temperature T_{GStd}, that
temperature-normalized quantitative dimension G_{Wkpc} +
$(T_{Std}-T_{Wkpc})$ x X_{Wkpc} - $(T_{GStd}-T_{GWkpc})$ x X_{Gage} that the workpiece
would measure to and by the selfsame gage means upon
such times as both the workpiece was to be at the first

10   predetermined reference temperature T_{Std} and the gage
means were was to be at the second predetermined,
reference, temperature T_{GStd}.

3.   The workpiece- and self-temperature
compensated dimensional measuring device according to

15   claim 2 wherein the second thermal sensing means
comprises:

a semiconductor temperature sensor mounted
to the gauge means.

4.   The workpiece-temperature-compensated

20   dimensional measuring device according to claim 1
wherein the gauge means comprises:

a three point snap gauge having two fixed
shoes and moveable measuring shoe.

5.   The workpiece-temperature-compensated

25   dimensional measuring device according to claim 4
wherein a one of the shoes of the snap gauge holds the
first thermal sensing means in thermal communication
with the workpiece.

6.   The workpiece-temperature-compensated

30   dimensional measuring device according to claim 4
wherein the three point snap gauge is thermally
insulated from a human hand by which it is held during
use to measure a workpiece.

7.   The workpiece-temperature-compensated

35   dimensional measuring device according to claim 1

wherein the dimensional measuring means comprises:

a three point rocker gauge emplaceable within a workpiece's bore for sensing the dimensions thereof.

8.   The workpiece-temperature-compensated dimensional measuring device according to claim 7 wherein the three point rocker gauge holds the first thermal sensing means in thermal communication with the interior wall of the workpiece's bore.

9.   The workpiece-temperature-compensated dimensional measuring device according to claim 1 wherein the first thermal sensing means comprises:

a thermistor.

10.   The workpiece-temperature-compensated dimensional measuring device according to claim 1 wherein the first thermal sensing means comprises:

a thermistor mounted to the gauge means in a position whereat it must be held in thermal communication with the workpiece upon such times as the dimensional measuring means is measuring the dimension of the workpiece, and is not merely incidentially held in thermal communication with the workpiece by the gauge means.

11.   The workpiece-temperature-compensated dimensional measuring device according to claim 10 wherein the first thermal sensing means further comprises:

a thermal insulating layer between the thermistor and the gauge means for reducing heat transfer between (i) the thermally communicating thermistor and workpiece and (ii) the gauge means.

12.   The workpiece-temperature-compensated dimensional measuring device according to claim 10 wherein the first thermal sensing means further comprises:

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a thermally conductive pad enhancing the
thermal communication of the thermistor with the
workpiece.

13. The workpiece-temperature-compensated
dimensional measuring device according to claim 12
wherein the thermally conductive pad comprises:
metal.

14. The workpiece-temperature-compensated
dimensional measuring device according to claim 13
wherein the metal comprises:
silver.

15. The workpiece-temperature-compensated
dimensional measuring device according to claim 1
wherein the computational means comprises:
a digital computer.

16. The workpiece-temperature-compensated
dimensional measuring device according to claim 1
further comprising:
display means for displaying the
temperature-normalized dimension of the workpiece.

17. A measuring instrument for indicating the
in-tolerance/out-of-tolerance condition of a
measurement made on a workpiece, the instrument
comprising:
gauge means for measuring the dimension of
a workpiece;
comparison means, receiving the measured
dimension from the gauge means, for comparing the
measured dimension to a predetermined dimensional
tolerance range about a predetermined reference
dimension;
indicator means, responsive to the
comparing of the comparison means, for indicating that,
by results of the comparing, the measured dimension is
either within or without the dimensional tolerance

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range.

18.   The instrument according to claim 17
further comprising:

range initialization means, communicating
with the comparison means, for variably predetermining
the dimensional tolerance range.

19.   The instrument according to claim 18
wherein the initialization means is manually actuable
for variably predetermining the dimensional tolerance
range.

20.   The instrument according to claim 18
wherein the initialization means is for separately
variably predetermining both upper and lower limits of
the dimensional tolerance range.

21.   The instrument according to claim 20
wherein the initialization means is manually actuable
for its separate variable predetermination of both
upper and lower limits of the dimensional tolerance
range.

22.   The instrument according to claim 17
further comprising:

reference dimension initialization means,
communicating with the comparison means, for variably
predetermining the reference dimension.

23.   The instrument according to claim 22
wherein the reference dimension initialization means
operates to set the reference dimension to the
dimension of a gauge block standard while the gauge
means is measuring the standard.

24.   The instrument according to claim 17
further comprising:

thermal sensing means, held by the gauge
means in thermal communication with the workpiece, for
measuring a temperature of the workpiece; and

wherein the comparison means further
receives the temperature measurement from the thermal
sensing means and is further for producing, in
consideration of a predetermined first dimensional
5   sensitivity of the workpiece to temperature variations
about a predetermined reference temperature, a
temperature-normalized dimension that the workpiece
would measure to and by the selfsame gauges upon such
times as the workpiece was to be at the predetermined
10:   reference temperature, this temperature-normalized
dimension being the measured dimension that is compared
to the predetermined dimensional range.

25.   The instrument according to claim 24
further comprising:
15   contact switch means, affixed to the
thermal sensing means in its position held by the gauge
means, for signalling when the thermal sensing means is
in good thermal contact with the workpiece; and
                indication disablement means, receiving
20   the contact signal from the contact switch means, for
disabling the indicating of the indicator means save
during the presence of the contact signal.

26.   The instrument according to claim 17
further comprising:
25   thermal sensing means in thermal
communication with the gauge means for measuring a
temperature of the gauge means; and
                wherein the comparison means is further
for receiving the temperature measurement from the
30   thermal sensing means and is further for producing, in
further consideration of a predetermined dimensional
sensitivity of the gauge means to variations in
temperature about the predetermined reference
temperature, that temperature-normalized dimension that
35   the workpiece would measure to and by the selfsame

gauge means upon such times as the gauge means was to be at the predetermined, reference, temperature, this temperature-normalized dimension being the measured dimension that is compared to the predetermined
5   dimensional range.

27.   The instrument according to claim 17 wherein the comparison means are further for determining, upon such times as the measured dimension is determined to be without the predetermined
10 dimensional tolerance range, whether the measured dimension is such that the workpiece is either (i) repairable so as to potentially be within the dimensional range, or (ii) unrepairable and subject to scrappage; and
15   wherein the indicator means are further responsive to the comparing for indicating that, by results of the comparing, the workpiece dimension is without the range of dimensions and, further, either (i) repairable so as to potentially be within the
20 predetermined dimensional tolerance range or (ii) unrepairable and subject to scrappage.
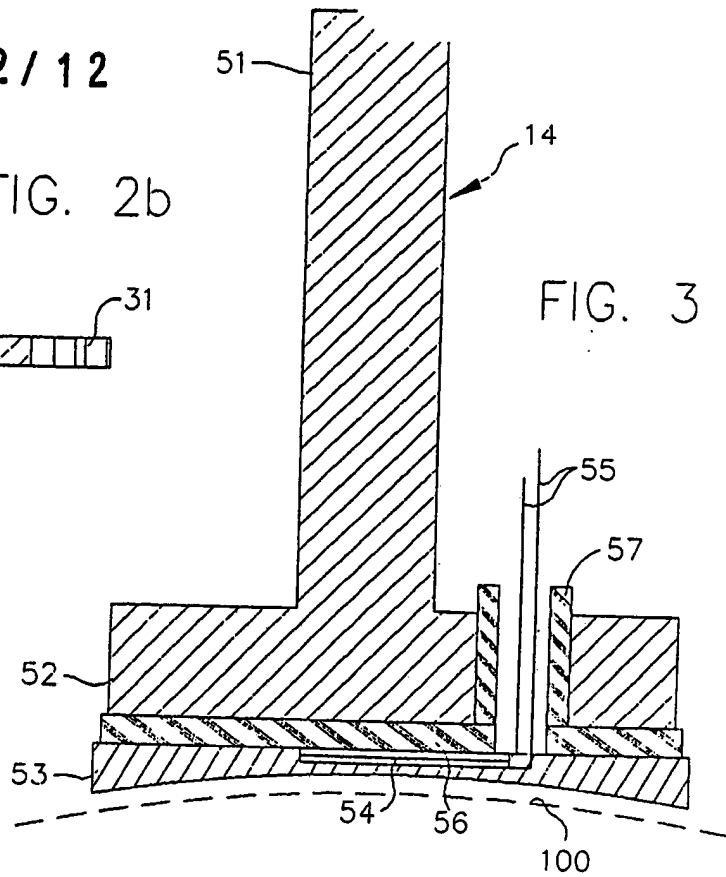

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30

35

FIG. 1

FIG. 2a

2 / 12

FIG. 2b

32

31

FIG. 3

51

14

55

57

52

53

54   56

100

TEMPETURE IN °F

85°F
85°F
75°F
70°F
65°F
60°F   STANDARD TEMP.
       FOR DIMENSIONING
55°F
50°F
45°F
40°F

104   101   102   103

6.1885   6.1895   6.1905   6.1915

SCRAP →|←—— REPAIRABLE ——→|←—— USABLE ——→|←— REPAIRABLE

FIG. 4   DIAMETER IN INCHES

FIG. 5

FIG.6

FIG. 7A

TO FIG. 7C

FIG. 7B

PUSH BUTTONS

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SW3 REFERENCE

SW4 SET LIMITS

SW1

SW2

SW5

DS1
GRN "OK"
DS2
YEL "REFURB"
DS3
RED "SCRAP"
DS4
GRN "TEMP MEASURE"
INDICATORS

RF1

230

FROM FIG. 7A

TO FIG. 7F

FIG. 7C   **7/12**

RP2

REF
SET
(+)
(−)

PA4
FA5
FA6
PA7

+5V

PA0
PA1
PA2
PA3

+5V

VDD

3800

R1   x1   C1

C2

PC0
PC1
PC3
PC3
PC4
PC5
PC6

68HC9__F4
MICROCONTROLLER

+5V

IRQ
PD5 SS
TCAP

NC
NC

PD6/TCMP
PD7
GND

FIG. 7D   8 / 12

FIG. 7E FROM FIG 7A

LOW VOLTAGE INHIBIT

FIG. 7E

FROM FIG. 7B

R40

R43

R42

701

2-SEC PWR
SW DETECT

P50

+2.5V REF

154

UNREG
180

P64

R29　R25

P27

P30

P31

FIG. 7F

WORKPIECE TEMP
SENSOR

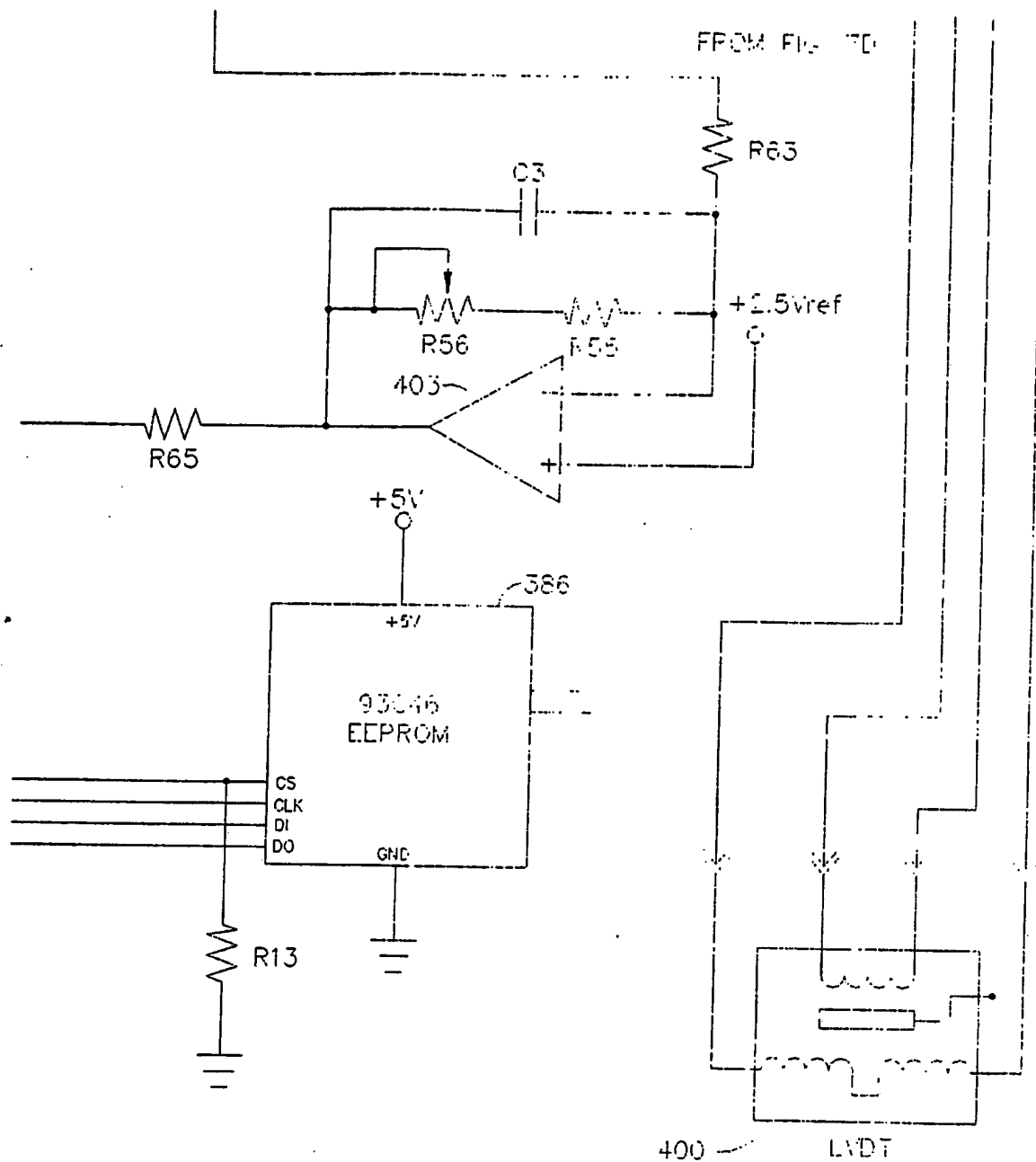1830

180

FIG. 7G

63HC68A2 A/D CONVERTER

FROM FIG. 7F

FROM FIG. 7G

FIG. 7H

INTERNATIONAL SEARCH REPORT

International Application No. PCT|US89|02639

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 6

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(4): G01B 7/12
U.S. CI: 33/178D, 702, 178F, 178E, 504; 374/56, 142; 364/571.03, 561, 5

II. FIELDS SEARCHED

563

Minimum Documentation Searched 7

Classification System	Classification Symbols
U.S.	33/702, 813, 819, 820, 504, 784, 178R, 178E, 178D, 178F, 827 374/55, 56, 142 364/571.03, 560, 561, 562, 563, 557

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched 8

III. DOCUMENTS CONSIDERED TO BE RELEVANT 9

Category *	Citation of Document, 11 with indication, where appropriate, of the relevant passages 12	Relevant to Claim No. 13
X	U.S.,A, 4,141,149 (GEORGE ET AL) 27 February 1979. See entire document	1-6, 9-10
Y	U.S.,A, 4,736,313 (NISHIMURA ET AL) 05 April 1988. See entire document	15, 16
A	U.S.,A, 4,443,945 (TAKEMURA ET AL) 24 April 1984. See entire document	
Y	U.S.,A, 2,222,336 (DOMELLOF) 19 November 1940 Fig. 2	6
A P	U.S.,A, 4,761,887 (BROWN ET AL) 9 August 1988	
A	U.S.,A, 3,311,986 (ZAWISTOWSKI) 4 April 1967.	
A	U.S.,A, 3,921,300 (COX ET AL) 25 November 1975	
A	U.S.,A, 4,389,788 (BALOGH ET AL) 28 June 1983	

* Special categories of cited documents: 10

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
01 AUGUST 1989	0 2 OCT 1989
International Searching Authority	Signature of Authorized Officer
ISA/US	*Diego F. F. Gutierrez* Diego F. F. Gutierrez

Form PCT/ISA/210 (second sheet) (Rev.11-87)

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE¹

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers   , because they relate to subject matter¹¹ not required to be searched by this Authority, namely:

2. ☐ Claim numbers....   , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out¹³, specifically:

3. ☐ Claim numbers_____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING²

This International Searching Authority found multiple inventions in this international application as follows:

  I. Claims 1-6, 9-16 drawn to a snap gauge type measuring device

  II. Claims 1-3, 7-16 drawn to a rocker type measuring device

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2. ☒ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

    1-16

3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (supplemental sheet (2) (Rev. 11-87)

Attachment to Form PCT/ISA/210, Part VI

III. Claims 17-27 drawn to a device for indicating the
     in-tolerance/out-of-tolerance condition of a
     measurement.